FLOODPLAIN INUNDATION. Alluvial channels and their floodplains behaved as functional units, with floodplains accommodating flows in excess of channel capacity. This had important ecological implications. First, as water overflowed from the channel onto the floodplain, it slowed down, because overbank flow was shallow and the floodplain was hydraulically rough, offering greater resistance to flow. Floodwaters charged with suspended sediment deposited some of the coarser part of their sediment load as they flowed overbank, typically leaving deposits of sand immediately adjacent to the channel (where the water velocity first slows) and finer grained sediment further away from the channel. Floodplain sedimentation is known to be important in alluvial rivers, responsible for measurable decreases in suspended sediment loads (Walling et al. 1998). From the point of view of water quality, the removal of suspended sediment from the water column is a potentially important effect.

Floodwater on the floodplains reduced the volume of floodwater in the channels and moved more slowly than water in the main channel. The net effect was to reduce the height of the flood wave as it moved downstream. Overflow onto the floodplain also served to limit the height of water in the channel, thus limiting the shear stress exerted on the bed. In essence, the floodplains acted as "pressure relief valves," which prevented a continuous increase in shear stress in the channel with increasing discharge. This permitted a larger range of sediment grain sizes to remain on the channel bed than would have been the case without overbank flooding because without overbank flooding, gravel may be mobilized and lost at the confined channel's higher shear stress. Similarly, overbank flows make more refuge habitat available to fish because there are zones of lower shear stress in the channel and because fish can seek refuge in the inundated floodplain.

Other important ecological interactions between the floodplain and channel include shading, food, and large woody debris provided by floodplain vegetation (Gregory et al. 1991, Murphy and Meehan 1991). During prolonged inundation of the Cosumnes River floodplain in 1997, salmon and other fish were observed feeding on the inundated floodplain, one illustration of the important migrations and interchanges of organisms, nutrients, and carbon that would have occurred frequently in the Bay-Delta system before 1850. Even along rivers where floodplain inundation was typically brief, interactions could be nonetheless important for recharging the alluvial water table, dispersing seeds of riparian plants, and increasing soil moisture on surfaces elevated above the dry season water table. Inundation of floodplains and maintenance of high alluvial water tables contributed to maintenance of floodplain aquatic habitats, such as side channels, oxbow lakes, and phreatic channels (Ward and Stanford 1995).

Floodplain soils and vegetation can also improve water quality in rivers by filtering sediments from runoff and by contributing to chemical reactions in the floodplain alluvium that can remove nitrogen and other constituents from agricultural or urban runoff.

ECOLOGICAL TRANSFORMATIONS FOLLOWING COLONIZATION

THRESHOLD EVENTS LEADING TO PRESENT CONDITIONS

GRAZING. Cattle were introduced in 1770 and rapidly expanded under Spanish rule. Along with the introduction of non-native annual grasses (which replaced most native bunch grasses), the reduction in upland plant cover, soil compaction, and reduction in riparian vegetation resulted in higher peak runoff for a given rainfall and higher erosion rates. This hydrologic transformation probably initiated a cycle of channel incision, with consequences on alluvial groundwater tables and wetlands.

GOLD MINING. Beginning about 1850, the extraction of gold transformed the channels and floodplains of many rivers, especially in the Sierra Nevada. Hydraulic mining, in which high-pressure jets of water were directed at gold-bearing gravel deposits (mostly on ridgetops), produced more than 1.67 billion cubic yards of debris, most of which was flushed from steep bedrock canyons onto the Sacramento Valley floor (Gilbert 1917). This massive influx of coarse sediment filled the river channels and spread out over floodplains, converting formerly silty farmland into gravel and sand deposits. Along the Yuba River upstream of Marysville, hydraulic mining debris created the Yuba River Debris Plain, encompassing more than 40 square miles. The bed of the Yuba River near Marysville aggraded about 90 feet, inducing the town to build levees. These could not contain the continually aggrading channel and were overtopped numerous times starting in 1875, resulting in extensive damage to the town. The increased sediment in the Sacramento River interfered with shipping and required dredging. Finer grained parts of the debris settled out in the San Francisco Estuary, adding to mudflats along the bay margins. Because of its downstream impacts, hydraulic mining was prohibited by court order in 1884, but the wave of hydraulic mining debris already in the system continued to progress downstream; the bed elevation of the Yuba River at Marysville peaked in 1905 and returned to estimated pre-mining levels by about 1950 (James 1991).

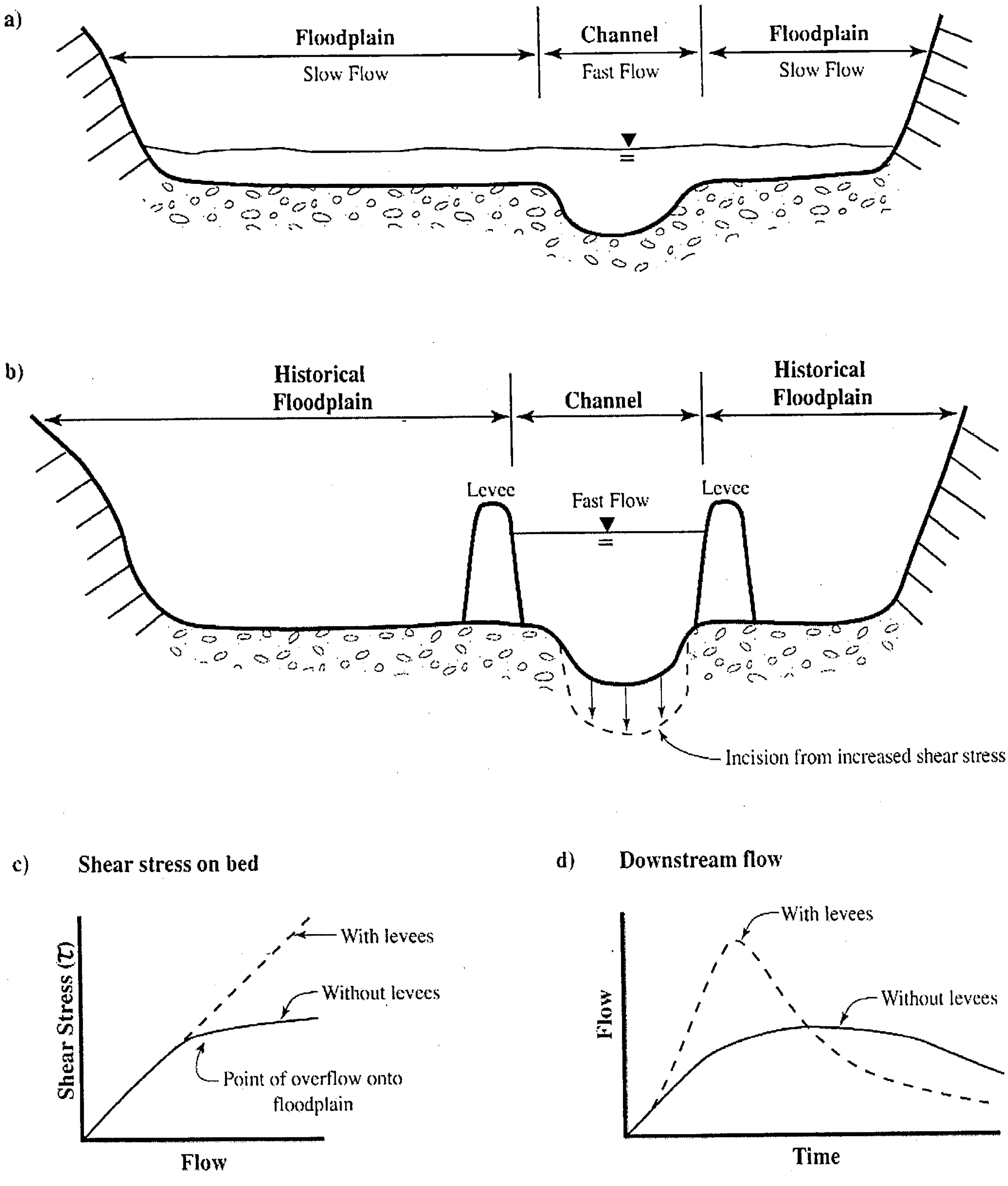
Gold-bearing floodplain and terrace gravels, including deposits of hydraulic mining debris, were extensively reworked by dredgers, which left linear mounds of tailings along many river channels in the Sacramento-San Joaquin River system. These dredger tailings have only coarse cobbles on the top, preventing establishment of vegetation except in low swales in between the tailing piles.

CHANNELIZATION FOR NAVIGATION. The Sacramento, Feather, and San Joaquin Rivers were important navigation routes, with ocean-going vessels reaching Marysville and Stockton in the 1850s. The influx of hydraulic mining sediment caused the rivers to become shallower, interfering with navigation. In response, riverbeds were dredged and levees were constructed along riverbanks (to concentrate flow and induce bed scour) to deepen channels. To facilitate navigation, large woody debris was cleared from many channels. To provide fuel for steamers, valley oaks and other trees were cleared from accessible areas near rivers.

ARTIFICIAL BANK PROTECTION. With increased agriculture and human settlement on the floodplain, it became more likely that natural channel migrations would threaten to undermine structures or productive agricultural land. To protect these resources, banks have been protected by riprap (and other artificial protection) along many reaches, including most of the Sacramento River downstream of Chico Landing. Riprapped banks effectively lock the channel in place, eliminate the contribution of gravels and woody debris from actively eroding riverbanks, and prevent the creation of new riverine habitats through meander migration. Moreover, the protected banks lack the overhanging vegetation and undercut banks (often termed "shaded riparian aquatic habitat") so important as fish habitat in natural channels (California State Lands Commission 1993). Riprap also damages the habitats of threatened and endangered bird species such as bank swallows.

LEVEE CONSTRUCTION. To protect floodplains against flooding, more than 5,000 miles of levees have been built in California, most of which are in the Bay-Delta system, and 1,100 of which are in the Delta itself (Mount 1995). Most of these are "close levees": levees built adjacent to the river channel itself (often on top of natural levees), in some cases to concentrate flow for navigation. By preventing overbank flows, levees reduce or eliminate interaction between channel and floodplain and thus reduce important ecological interactions. In addition, by eliminating overbank flows and natural floodplain storage, levees concentrate flow in the main channel, which results in greater depths, faster flow, and higher flood peaks downstream (Figure A-2) (IFMRC 1994).

FLOODPLAIN CONVERSION. Most floodplains, with their fertility enhanced by overbank silt deposits, were converted from alluvial forest or riparian marsh to agricultural land, with subsequent conversion of many areas to urban use. Valley oak woodlands were cleared extensively because they tended to occur on good soils. First cleared along the Sacramento River were the well-drained, broad, linear ridges (natural levees) developed along the current and former channels from overbank deposits. Then of lower flood basin areas were converted as they were drained and diked off from frequent floods. The floodplains of the Sacramento and San Joaquin Rivers were extensively cleared in the second half of the 19th century for dryland wheat farming, which occupied 3.75 million acres in 1880s (Kelley 1989). In the Sacramento Valley, rice growing developed since



Note: With natural floodplain functioning, much of the floodwaters are accommodated on the floodplain, where high hydraulic roughness leads to slower flows and thus slower downstream transmission of floodwaters (a). Levees concentrate floodwaters in the channel (b), resulting in deeper water and higher velocities, faster downstream transmission of floodwaters, and higher flood peaks downstream (d). Deeper and faster flows lead to higher shear stresses (force per unit area) on the channel bed (c), which may lead to bed incision (b).

Figure A-2: Effect of Levees on Floodflows and Channel Geomorphology

1910 with levee construction and availability of irrigation water, with 600,000 acres of rice in flood basins by 1981 (Bay Institute 1998).

Unfortunately, no reliable data exist on the actual extent of riparian forest before 1850, and estimates vary widely. The potential maximum area of riparian forest in the Sacramento Valley (based on soils and historically mapped riparian forest) was 364,000 acres. Only about 38,000 acres exist today, approximately 10% of the historical value. However, it is unlikely that the forest ever occupied the full 364,000 acres at one time (Bay Institute 1998). In the San Joaquin Valley, soils and historical accounts suggest a potential pre-1850 riparian zone of 329,000 acres, contrasting with a current 55,000 acres of wetlands and 16,000 acres of riparian forest (Bay Institute 1998). The area currently mapped as riparian forest includes areas of poor quality, heavily affected by human action. An illustration of a relatively recent conversion of floodplain habitats in the San Joaquin River basin is shown in Figure A-3. On the floodplain of the Merced River, a complex of side channel habitats was eliminated for agriculture between 1937 and 1967.

TIDAL MARSH CONVERSION. In the Delta and Suisun, San Pablo, and San Francisco Bays, similar transformations were underway, with most former tidal marsh and mudflats converted to agricultural lands (and some to urban uses). In the Delta, there was an estimated 380,000 acres of intertidal wetlands, 145,000 acres of nontidal wetland, and 42,000 acres of riparian vegetation on higher ground (Bay Institute 1998). Today, about 21,000 acres of wetland remain, of which about 8,200 acres are tidal (San Francisco Estuary Project 1992). The tidal wetland loss was largely finished by 1940 (Atwater et al. 1979).

The loss of these wetlands can be considered one of the most significant human-caused functional modifications of the Bay-Delta ecosystem. The Delta tidal marshes probably formed an important link in the nutrient transfer between the riverine and open-water estuarine components of the watershed. Delta tidal marshes had the highest primary productivity and biodiversity of any comparably sized area in pre-Columbian California. Although exports from marshes to adjacent open water systems have been difficult to demonstrate (Mitch and Gosselink 1993), it is likely that the Delta tidal marshes functioned as a filter that trapped sediment and removed inorganic nutrients supplied by the rivers from the upstream watershed and produced organic inputs that were transferred to the bay. Currently, tidal marshes probably still remove inorganic and organic compounds (including toxins) from the rivers, but this function has been greatly reduced because the existing river system largely bypasses the marshes.

The loss of networks of shallow dendritic slough channels in the tidal marsh has greatly reduced the length of the linear interface between open water and vegetated marsh. Historical topographic maps show that the drainage pattern in historical tidal marshes was much more complex than in current, remnant tidal marshes. Historically, tidal marshes probably provided important feeding and reproduction habitat for many vertebrate species. Restoration of tidal marsh will be most beneficial to vertebrate species if both tidal marsh area and habitat complexity are restored. Similarly, these shallow-water habitats were formerly exposed to a variable salinity regime to which native species were adapted.

RESERVOIRS AND DIVERSIONS. Dams constitute important discontinuities in rivers, altering riverflows, eliminating the continuity of aquatic and riparian habitat, and blocking migration of fish and other organisms. Reservoirs impound water for many reasons, such as generation of hydroelectric power; flood storage; and controlling flow to allow diversions, increased consumptive use, and export. Dams have cut off upper reaches of rivers, hydrologically isolating them (Figure A-4). One implication of this fact is that most of the channels of concern to CALFED lie downstream of large reservoirs and are thus hydrologically isolated from changes in runoff or sediment load in the upper reaches of the watersheds. For example, increased erosion from timber harvest or changes in water yield from changes in vegetative cover in the upper Feather River tributaries will not affect conditions in the ERP focus area downstream of Oroville Dam as long as the reservoir continues to trap sediment and regulate flows.

As barriers to migration, dams have had an especially hard impact on spring-run chinook

1937

1967

Figure A-3: Aerial Photographs of the Merced River Floodplain, Showing Loss of Floodplain Side Channel Habitats from 1937 to 1967.

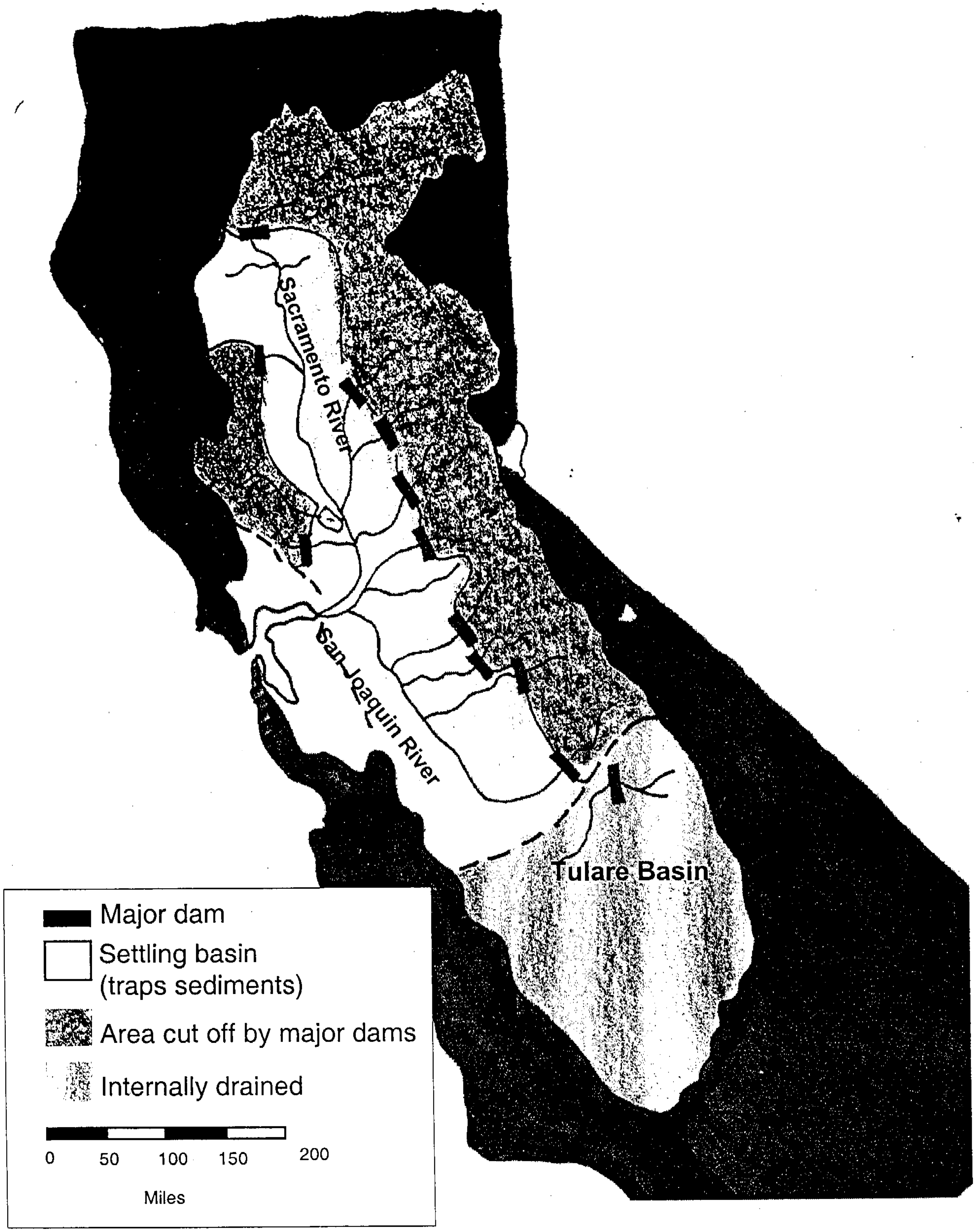


Figure A-4: Upper Watersheds in the CALFED Solution Area Cut off from the Lowland Alluvial Rivers by Dams salmon and steelhead trout, which formerly migrated to upstream reaches to spawn. In the San Joaquin Valley, Friant Dam delivered the entire flow of the upper San Joaquin River south, abruptly eliminating a major run of Chinook salmon. The extent of river channel inhabited by spring-run salmon has decreased dramatically since the early 19th century (Figure A-5). Overall, reservoirs were found to be the most important gaps in riparian habitat in rivers draining the Sierra Nevada (Kondolf et al. 1996). Diversions also entrain fish, resulting in direct mortality, especially of juveniles.

By 1940, most rivers in the Sacramento-San Joaquin River system had dams large enough to block fish passage, reduce flows during critical baseflow periods, and reduce frequent floods. However, reservoir size and cumulative reservoir storage increased dramatically with construction of the Central Valley Project, the State Water Project, and other large dams. From 1920 to 1985, total reservoir storage capacity increased from about 2 million acre-feet to 30 million acre-feet (Figure A-6) (San Francisco Estuary Project 1992, Bay Institute 1998). Reservoir storage in the Sacramento River system is now equivalent to 80% of annual average runoff; in the San Joaquin River system, reservoir storage is equivalent to 135% of runoff. As a result of dams, diversions, consumptive use, and export out of the watershed, the total runoff to the San Francisco Bay from the Delta has been reduced from pre-1940 runoff by 30-60% in all but wet years (Nichols et al. 1986, Bay Institute 1998). The seasonal distribution of flows has fundamentally changed, and flood magnitude and frequency profoundly decreased. The mean annual flood (the average of annual peak flows) has decreased by 20-65 % from pre-dam values (depending on reservoir capacity in relation to runoff) (Table A-1).

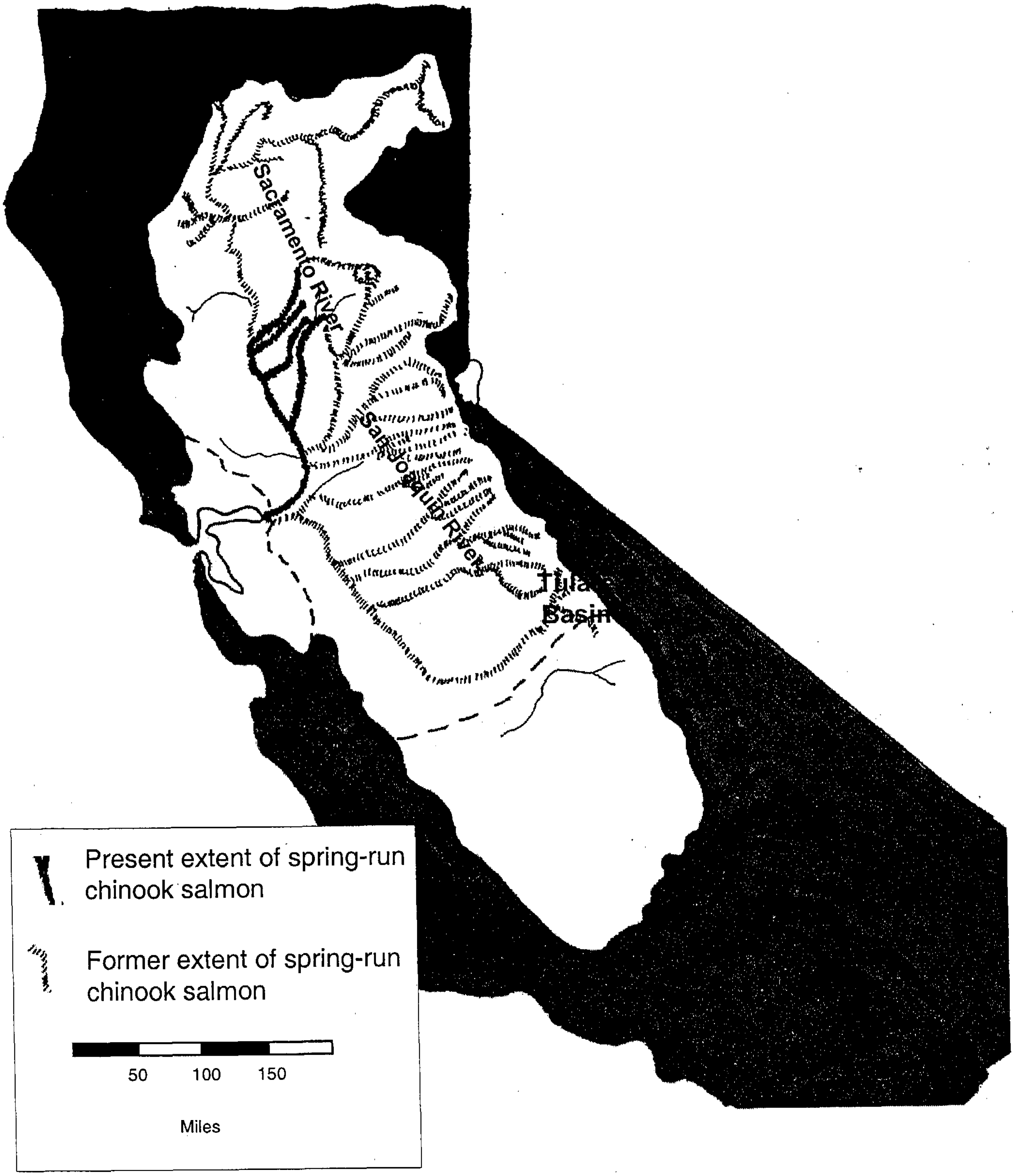
The reduction in floodflows has transformed river channels of the Sacramento-San Joaquin system. Rates of bank erosion and channel migration in the Sacramento River have declined because of dam construction and construction of downstream bank protection projects (Brice 1977, Buer 1984). The channel sinuosity (ratio of channel length to valley length) has also decreased because of numerous meander cutoffs (Brice 1977), reducing total channel length and thus total in-channel habitat. Moreover, the diversity of riparian and aquatic habitats is directly related to the processes of bank erosion, point bar building (creating fresh surfaces for riparian establishment), and overbank deposition, resulting in a mosaic of different-aged vegetation and contributing to the complexity of in-channel habitat and shaded bank cover (California State Lands Commission 1993). The reduction in active channel dynamics is compounded by the physical effects of riprap bank protection structures which typically eliminate shaded bank habitat and associated deep pools, as well as halting the natural processes of channel migration.

Reduced floodflows below dams have also rendered inactive much of the formerly active channel, "fossilizing" gravel bars and permitting establishment of woody riparian vegetation within the formerly active channel, narrowing the active channel and reducing its complexity (Peltzman 1973, Kondolf and Wilcock 1996). The reduced frequency of formerly periodic flood disturbance in channels downstream of dams has created conditions favorable to establishment of exotic species (Baltz and Moyle 1993).

Elimination of annual floodflows below dams may permit fine sediment to accumulate in gravel beds and cobble beds, reducing the quality of spawning and juvenile habitat for salmonids, and invertebrate production (Kondolf and Wilcock 1996). Reduced mobility of gravel beds may also favor invertebrate species less desirable as food for salmonids (Wootten et al. 1996).

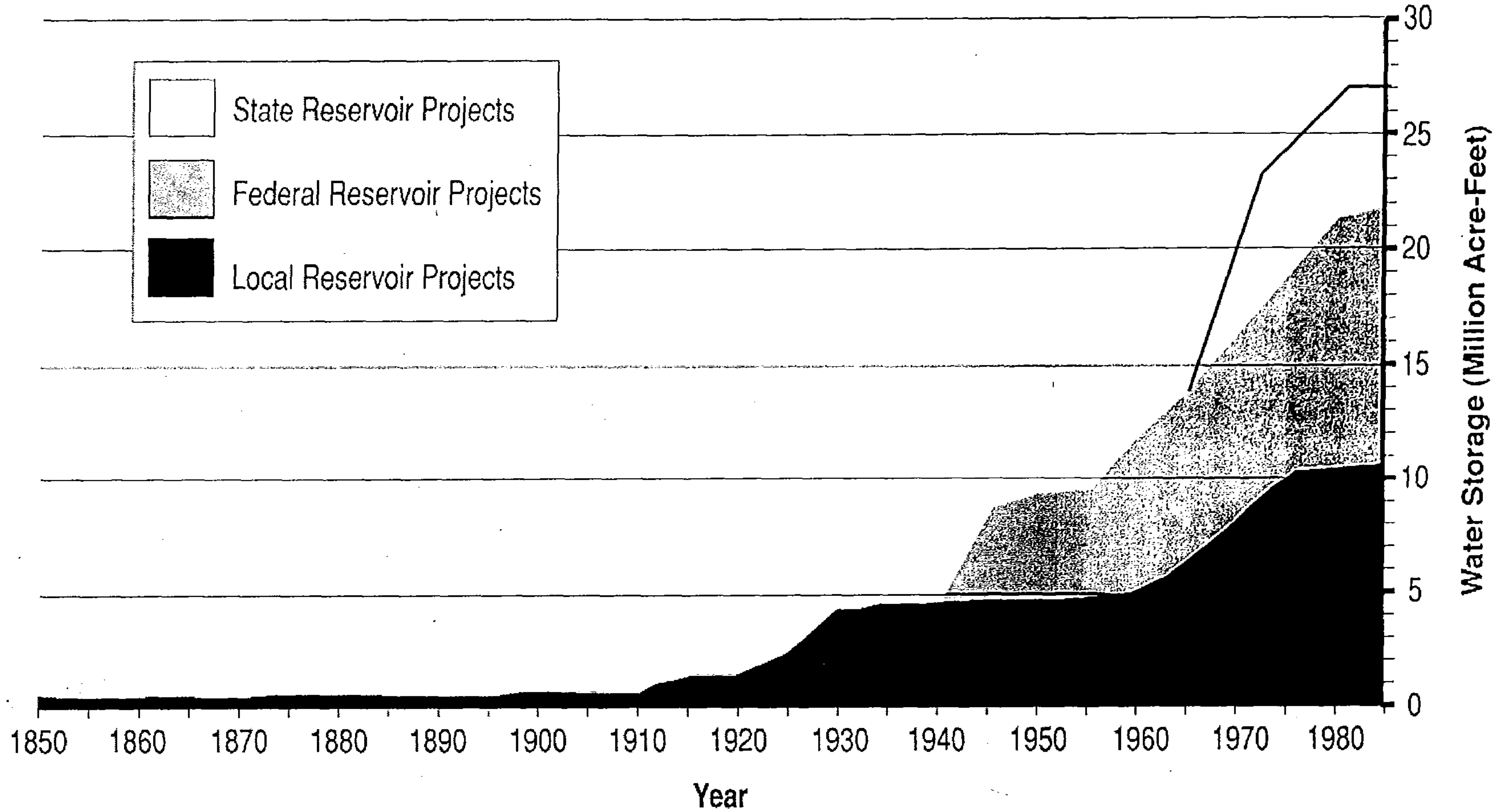
Dams also trap sediment derived from upstream, commonly releasing sediment-starved water downstream, as discussed below.

EXTRACTION OF SAND AND GRAVEL FOR CONSTRUCTION AGGREGATE. The rapid urbanization of California has required massive amounts of sand and gravel for construction aggregate (e.g., road fill, drain rock, concrete for highways, bridges, foundations), with annual production of more than 100 million tons, 30% of the national production (Tepordei 1992). Nearly all this sand and gravel is drawn from river channels and floodplains. Mining in channels disrupts channel form, causes a sediment deficit and channel incision, with resulting loss of



Source: Kondolf pers. comm.

Figure A-5: Present versus Historic Extent of Spring-Run Chinook Salmon



Source: San Francisco Estuary Project 1992.

Figure A-6: Cumulative Increase in Reservoir Storage in the Bay-Delta System

TABLE A-1. CHANGES IN MEAN ANNUAL FLOWS FOR SELECTED RIVERS IN THE SACRAMENTO-SAN JOAQUIN RIVER SYSTEM

River	Dam	Date Constructed	Gauge Number	Period of Gauge Record	Mean Annual Flood (cubic feet per second)		Percent Reduction
					Pre-dam	Post-dam	
Sacramento River	Shasta	1945	11377100	1938-1996	120,911	78,885	35
Feather River	Oroville	1968	11407000	1902-1996	69,641	22,929	66
American River	Folsom	1956	11446500	1904-1996	53,459	29,651	45
Stony Creek	Black Butte	1963	11388000	1955-1990	13,744	7,959	42
Mokelumne River	Camanche	1963	11323500	1904-1996	7,395	2,431	66
Stanislaus River	New Melones	1979	11302000	1957-1996	10,016	3,135	69
Merced River	New Exchequer	1967	11270900	1901-1996	8,287	4,560	45
San Joaquin River	Friant	1942	11251000	1908-1996	18,614	3,718	80

Source: U.S. Geological Survey.

spawning gravels and other habitats. Floodplain gravel pits commonly capture the river channel (i.e., the river changes course to flow through the pits). The pits are excellent habitat for warmwater species that prey on salmon smolts; the California Department of Fish and Game estimates that 70% of the smolts in the Tuolumne River are lost to predation annually (EA Engineering, Science, and Technology 1992). Refilling these pits to eliminate predator habitat and restore channel confinement is expensive, with $5 million recently budgeted to fix two such pits on the Tuolumne River.

SEDIMENT STARVATION FROM DAMS AND GRAVEL MINING. Dams and gravel mining can result in a sediment deficit downstream, especially when mining occurs downstream of dams. The cumulative effect of sediment trapping by dams has been enormous. Using published reservoir sedimentation rates, and assuming sand and gravel to be 10% of total sediment load, we estimate that the mountainous reaches of the Sacramento, San Joaquin, and tributary rivers formerly delivered an annual average of about 1.3 million cubic meters to the Sacramento and San Joaquin Valleys. (This is the estimated sediment yield to the large foothill reservoirs, or to the equivalent point in an unregulated river, near the transition from mountainous upland to valley floor.) Construction of reservoirs has cut this amount to about 0.24 million cubic meters, a reduction of about 83%. This does not account for the further reduction in sediment budget from gravel mining in the channels in the valley floor.

Overall, the rate of gravel mining from rivers in California is at least 10 times greater than the natural rates at which gravel and sand are eroded from the landscape and supplied to the rivers (Kondolf 1997). On the Merced River, an estimated 150,00-300,00 tons of sediment have been trapped behind the Exchequer Dam since 1926, and 7-14 million tons of sand and gravel have been excavated from the channel and floodplain since the 1950s (Kondolf et al. 1996). This constitutes a profound alteration in the regime of rivers tributary to the Bay-Delta. Although some of the sediment deficit is made up in the short term through bank erosion and channel downcutting and the transport capacity of most rivers has been reduced by reduced floodflows, the magnitude of the overall reduction in sediment supply to the system is such that long-term adjustments in channel, floodplain, and intertidal marsh/mudflat habitats are inevitable.

Dams, gravel mining, and bank protection have so reduced the supply of gravel in the Sacramento River system that many reaches of river that formerly had suitable gravels for salmon spawning are no longer suitable for spawning (e.g., Parfit and Buer 1980). In the CALFED area alone, millions of dollars have already been spent and will be spent to add gravels (and create spawning riffles) in the Sacramento, Feather, American, Mokelumne, Stanislaus, Tuolumne, and Merced Rivers and in Clear and Mill Creeks, all in attempts to compensate for the loss of spawning habitat (Kondolf and Matthews 1993, Kondolf et al. 1996).

OVERFISHING. Fish populations have been directly affected by harvest rate, most notably the intensive harvesting of the late 19th century, with development of major commercial fisheries for salmon in the estuary and the rivers. Gill nets strung across the Sacramento River at times completely blocked access to spawning grounds. Dozens of salmon canneries sprang up along the estuary, but the last one had closed by 1916, after the runs were depleted. Sturgeon were caught in the salmon nets in large numbers and most were killed and discarded because of the damage done to the nets. Commercial fisheries also developed to catch resident fishes, such as Sacramento perch, thicktail chub, and others, which were sold as fresh fish in the markets of San Francisco.

The early 1900s marked the beginning of the era of some of the first conservation legislation at state and national levels, the sturgeon fishery was banned, salmon populations were allowed to recover, and refuges were set aside for waterfowl.

EFFECTS OF WATER DIVERSIONS FROM THE DELTA ON NATIVE FISHES. Water diversions from the Delta affect fish in two principle ways, the direct diversion of fish and adverse effects on Delta channel hydraulics.

Delta diversions result in losses of all life stages of fish, particularly eggs, larvae, and juveniles as well as the loss of nutrients and primary and secondary